"Memories and thoughts on 50 years of oil and gas geophysics"

Jean Laherrere ASPO (Association for the study of peak oil and gas)

March 2005

« All that is simple is false and all that is complex is useless » Paul Valéry

Seismic was born during the First World War when the German military (led by Mintrop who founded Seismos in 1921) located Allied guns by measuring the acoustic waves. French and English attempts were less advanced to locate German guns. Seismos, the oldest geophysical contracting company in the world, applied the refraction shooting to the exploration of salt domes in Germany. Karcher (who founded GSI later) carried the first reflection survey in 1921 in Oklahoma. Gravimetry was introduced in 1915 by Eostvos in Czechoslavia and during the 20s on the salt domes in Texas. Geophysics in well (logging) started in 1927 in France by the Schlumberger brothers in Alsace.

I have lived through most part of the world geophysics evolution

I joined Compagnie Francaise des Petroles (now Total) in 1955 after studies in Ecole Polytechnique and Ecole Nationale des Petroles. I was sent to the Sahara as geophysicist in 1956 where I participated in the discovery of Hassi Messaoud and Hassi R'Mel, the largest oil and gas fields in Africa. We were using refraction shooting tracking the basement, despite that being of a lower velocity than the anhydrite (Mesozoic), but it is more energetic at long distances (10 km), also measuring gravity and airmag. Reflection shooting was used to get more precise mapping of the horizons, but reflections were too weak within many multiples events and too discontinuous to be tracked below the anhydrite. I measured the anisotropy (Dunoyer, Laherrere 1959) of the sediments with a model based on the first CVL (Continuous Velocity Logging where the signal was picked directly by the operator) shooting at the surface of 4 tons of nitrate plus fuel 15 km away from the well in which a geophone was located in the basement. I calibrated with difficulty reflection events by synthetic seismograms (Laherrere 1961). I saw the conversion from analog recording on films to magnetic tape (1957 Carter) and digital recording (1964). The largest progress in reflection recording was the CDP (common depth point) (or CMP = common midpoint) in 1962 where, thanks to magnetic recording, addition of many different ray paths reflecting at the same point from different source and receiver position could enhance the signal over the noise ratio. From the desert of Sahara, I moved to the deserts of Australia where I combined reflection and refraction (offset shooting) as well as gravity. Later on I went to the white deserts of Canadian Northern Territories, to search for reefs in Michigan or to drill among the icebergs in Labrador. After 15 years overseas, heading the research and technical assistance in the Paris headquarters and member of the CGG (Compagnie Generale de Geophysique) board, led me to get involved in worldwide geophysics. As President of the Exploration Commission of the Technical Committee of UFIP, I pushed for the publication of a dozen of manuals.

Retired since 1992 I write and present papers on oil and gas reserves, future production and natural distributions (http://www.oilcrisis.com/laherrere) but my unique opportunity to look at seismic profiles is in main exploration magazines.

What are the main results of these 50 years of geophysics?

-surveying

Surveying is a very important part of geophysics, as it is imperative that the drilling is being done at the right location. In the old days, in deserts with no infrastructure, it was first necessary to install an astronomic point by looking at the sun and stars for several days. Offshore, a navigation system was installed during all the exploration with several stations transmitting signals from around the area. Now GPS has changed it all and it is a huge progress. Positioning is easier and of much better quality.

-data storage

The first films or playbacks from Carter tapes, which was burning a special paper, were very cumbersome but easier to recover than the first magnetic tapes, as their drivers do not exist anymore. Magnetic tape, optical disk, CD and all modern storage supports, despite what advertisements say, deteriorate with time and suffer the obsolescence of drivers and software. Data storage is the major problem unsolved for a long-term preservation

-addition of different surveys

Adding up different seismic surveys is a nightmare as the surveying bases can be different as well as the seismic equipments. The prime interest of 3D is mainly that previous 2D surveys could be thrown away

-sources

In the search of data improvement, the source is important and practically everything has been tried; on land deep holes, multiple shallow holes (over 100 covering one hectare in the Sahara), nitrate shooting on surface or on 2 meters poles, weight dropping, Mini Sosie Sourcile, vibration (first with eccentric weights). VibraSeis has the reputation of causing the minimum damage. Offshore first with dynamite (Flexichoc), electric arc (sparker), steam (Vaporchoc), water gun and now airgun. The piezoelectric sources are used in wells.

-geophones

It is always the same coil suspended in a magnetic field and geophones have changed little in the last 50 years. It is the transmission to the recording unit, which has changed a lot when analog transmission by pair of cables (one per stations) was replaced by the telemetry able to transfer hundreds of channels by only two pairs. Recording S waves (geophones from 3 directions) did not get the expected success on land, but it seems more successful offshore with cables laid on seafloor for the 4D monitoring where the price of the sensors does not matter much

-processing

It is where all has changed and where progress will continue with better models and faster computers. But we must recognize the simplest assumptions as only P waves, perfect and homogeneous reflectors, no absorption, near horizontal layers, no lateral velocity variation works in 90% of the cases. And when it does not work, a more complex approach is difficult to adjust and results are often below expectations.

-surface corrections or static corrections

All recordings by geophones on a variable topographic surface must be corrected in propagation time to a reference level by removing the surface heterogeneities. Certain areas present some important near surface variations, which distort deep reflections. In Michigan the effect of the erratic glacial moraine deposits were solved during the 70s by flattening on an upper reflector to show the deeper pinnacles of Silurian reefs. In the Paris Basin, the velocity variations in the chalk were difficult to solve, requiring a complete mapping of the chalk. Computer now makes it possible to work with many data and complex models to improve static corrections.

-depth map

Time maps could have a different shape compared to depth maps. Velocities are estimated from the curvature of the reflectors with distance (neglecting the anisotropy). However reflectors are assumed to be near horizontal and addition (stacking) is performed at the vertical of the CDP. Now stacking of multiple paths are done after migration and depth conversion (prestack depth migration) thanks to a more accurate velocity model and powerful computers. But the knowledge of velocity, which has well progressed (mainly with trial and error), still needs to improve in complex and new areas. It is good to remind that there are as many depth maps as velocity, models which building requires a great collaboration with geologists.

-frequency

Explosion gives a very large spectrum, but very quickly the sediments filter high frequencies, in particular the loose surface sediments and more than often only low frequencies from 10 to 100 cycles per second (hertz) are recorded. Lower frequencies cannot be recorded with a small geophone and in refraction shooting larger and heavier geophones are used to get lower frequencies. It is difficult to increase the range of frequencies and only some exceptional areas allow getting a large range. To get the high frequencies needed to interpret thin reservoirs, recording with a source in one well and with geophone in a near well has been disappointing because poor source and tube waves.

-amplitude

Seismic amplitudes received by geophones show a very large range between the strong arrivals (often less interesting) and the weak arrivals from the deep reflections. With analog recording it was necessary to use an automatic gain control, which was bringing instrument distortions. With digital recording, all the range is correctly recorded but should be manipulated in order to get a visual display.

-resolution

Search for structures is all relative. Time sections easily evidence closure of more than 10 ms (milliseconds). Assuming an average velocity of 3000 m/s this corresponds to a closure of 15 m, but we should accept a poor accuracy on the total depth of this closure. The thickness of a reservoir depends upon the frequency of the reflection. For a frequency of 50 hertz the wavelength is 20 ms (double time) and only a minimum thickness of 5 ms (one quarter wave length) can be seen. For sandstones with a velocity of 4000 m/s this gives a minimum thickness of 10 m: thin sands are badly seen on seismic. To improve the resolution, frequencies have to be increased, and little progress has been made in the last 50 years on this matter because it is difficult to get rid of the surface sediments (putting geophones below is impracticable). Resolution and number of digits are often confused. Using computer provides many digits and many authors publish more than three digits when accuracy is no better than 10%. In geophysics no more than 2 or 3 digits should be given. GIGO "garbage in, garbage out" is often forgotten, and coming from a computer, it is often "garbage in, gospel out"!

-noise

CDP is the largest progress in seismic recording because it suppresses noises compared to seismic signal by a factor being the square root of the n level of the coverage (reflector amplitude on the common point is multiplied by n, when random noise by square root of n).

Any unexplained or unwanted event is called noise and is eliminated with all available processes. Unfortunately a part of the so-called noise is in fact useful data, but which cannot be extracted, as refracted event or converted P-S wave, or cannot be interpreted.

-multiples

High amplitude and shallow events give inconvenient multiples, but they are easily eliminated when velocity of the upper horizons are low (case of water) compared to deep horizons.

-diffractions

Any singular acoustic point, such as a fault receiving a seismic wave, becomes a secondary source and send disturbing arrivals = diffractions. These diffractions are partly eliminated through processing, but they should be better studied to reconstitute these singular points outlining particular fault plans.

-sinusoid = sine wave

A change in acoustic impedance (velocity-density product) is transformed, in the sediments, in a sinus wave. This transformation of rock properties into a wiggle is simulated by a synthetic seismogram obtained by convolution a wavelet by the velocity-density contrasts. The reversed approach (inversion) is aimed at obtaining from a seismic record the log of acoustic impedance. Unfortunately seismic data are band limited and very low, since high frequencies are missing. The goal to get rid of the sine wave was not reached; the only progress was to better display layers in blue and red instead of peaks and troughs.

-velocity

The definition of velocity is relative and in practice there are as many velocities as ways of measurements and as types of waves. There are P, S, Rayleigh, Love, Stonely waves among others. Happily the P waves are the simplest and the strongest ones. The velocity to convert a time map into a depth map depends upon the surface corrections, the datum plane, the processing applied, the picking (peak or trough) and the calibration. The velocities from seismic processing to compensate from the curvature of reflectors with offset (distance of the geophones from the source) have no real physical meaning, for they are the parameters of the implied model. Despite velocity from logging (Sonic) in the hole uses frequencies and distances very different from the surface seismic, is happily fairly close after integration to the measurements from a check shot survey with a geophone in the well. The velocity from core (with different pressure and temperature conditions) is punctual and only indicative. In fact nobody knows very well what is causing the sediments acoustic velocity, logging experts talk about «tortuosity», term unknown to surface geophysicists, which depends upon the pores and the contact points of the sediment grains. There are still many unknowns in velocity. I know that I do not know!

-deconvolution

As mentioned above, the reduced frequency range handicaps the efficiency of the deconvolution and there is little hope to increase such range.

-bright spots, flat spots, AVO

The amplitude of a reflector varies upon the thickness of the layer which generates the reflection, the physics of this layer = sediments and its fluid content. At the end of the 60s Exxon found that reservoirs with oil and gas presented some amplitude anomalies called « bright spots ». In 1973 during the sale of new offshore blocks in the Mississippi, Alabama and Florida States on the « Destin dome » Exxon spent 1.5 G$ (the first oil shock was providing a lot of funds) to acquire very far from any wells leases showing many « bright spots » which resulted in a dozen of dry wells. Industry discovered soon after (Domenico 1976) that the presence of a small amount (5%) of gas (lemonade or Fizz water) was enough to lower the velocity of those layers, giving bright spots. Fortunately commercial oil and gas often present bright spots, quite used in the Gulf of Mexico and elsewhere.

It is the same phenomena with Fizz water, which explains the famous reflector BSR (Bottom Simulating Reflector) found in some places in oceanic seismic lines used for the drilling of JOIDES-ODP (Ocean Drilling Program) wells. This BSR was assumed to come from the presence of hydrates and many geoscientists were seeing huge volumes of oceanic hydrates (Laherrere 2000). But drilling found BSR without hydrate and hydrate without BSR. The BSR comes from the presence of 1 to 5% of free gas (measured by ODP on leg 164 on Blake Ridge, offshore Carolina State) in sediments below the stability zone of the hydrates (about 500 m below the deep seafloor depending pressure and temperature).
In producing basins, the gas-oil contact and /or oil-water contact may provide sometimes a «flat spot» which happily is different from sediments reflections.
The analysis of the amplitudes with offset (AVO) is also used to obtain information on sediments and fluids. But there are many successes and many failures.
The direct hydrocarbons indicators (DHI) must be used carefully, requiring a nearby well to calibrate them.

-well calibration, synthetic seismogram, VSP

Any interpretation of seismic surveys is only reliable if it is calibrated by one or several wells. The calibration first requires to have a seismic line across the well, second a continuous velocity logging (Sonic) and third and a checkshot giving the times from the surface shooting to the depth of the main reflectors where a geophone is set up. The continuous velocity plus density log is convoluted with an average wavelet (or a wavelet varying with depth) to compute the synthetic seismogram, which should correlate to the seismic line at well location. But the likeness is sometimes good, sometimes poor. The shooting of a VSP (Vertical Seismic Profile, technique coming from the Russians) was assumed to improve the calibration, but the results were not worth the hopes. Most of articles that I see now in AAPG, Geophysics, EAEG, MPG and others as well the adverts on AAPG Explorer (which are assumed to show the best sections) almost never display a well calibration with a Sonic log in time, only the main geological names are superimposed! Hopefully there is a potential progress for the next generation of geophysicists.

-**Sonic**

The CVL (Continuous Velocity Logging), tool for geophysicists, which was the first to record well velocity for many years, was replaced by the Sonic, a tool for geologists.
In the Sonic picking of the main event is automatic (certain level), ignoring amplitude change and secondary events are ignored, while with the CVL and the manual picking the poor geophysicist was seeing a lot of interesting events that he was unable to record.
The Sonic was adopted by geologists because it was a porosity tool, but made geophysicists lose 20 years before better understanding velocities. Tools like EVA (SNPA-Elf) in the 70s (but too complicated) and like DSI, brought some progress in the study of seismic waves in wells. However logging is done long after drilling and damage to the formation disturbs the measures. Now with the MWD (measuring when drilling) measures are taken before any damage is done.

-**S waves**

Transverse or S waves need geophones to be placed transversally to record them. S waves are not changed by fluids and allow distinguishing fluid effects from lithology effects when compared to P waves (longitudinal or compression waves). S waves are not disturbed by gas chimneys. Many hopes were placed in the S waves to obtain fluids and lithology (Poisson coefficient), but progress was slow.

-refraction
As already mentioned the first seismic surveys were with refraction but reflection surveys were more precise and easier to interpret, so refraction surveying was abandoned. However the supergiant oilfield Hassi Messaoud (10 Gb) was discovered with refraction in the 50s as reflection was unable to record any reliable events at the reservoir (Cambrian quartzitic sandstone) level due to the strong absorption by the above thick salt formation and the interference with multiples. It was in the 50s impossible to pick a reliable event at the reservoir level. I bet 5 years ago on the web to pay a dinner in the best Paris restaurant to anyone who can show me a reflection profile across Hassi Messaoud showing without any well a reliable structure. One expert called me last year to tell me that he will show me soon such a recent reflection profile, but later he gave up. Maybe I will lose one day!
After drilling a well in a volcanic body offshore the Amazon delta in Brazil based on an interpretation of sand deposits from reflection seismic, we found in old literature some Lamont refraction shootings showing at the planned objective high velocities, which was against the sand hypothesis. Too late!
If reflection gives more details on sediments, it is unable to pick for sure where the basement is (high velocity), while it is easy for refraction. Since reflection shooting is recorded with long (mainly offshore) refraction events are captured though most of the time they are rejected as not being part of the reflection processing. In 1965 (Laherrere, Drayton) in the Simpson Desert in Australia using reflection long offset shooting we were able to obtain refraction events to follow the basement and to interpret across a fault where the correlation was difficult. The Permian objective was missing (the reflection was in fact a multiple), leading to condemn the area without drilling. We dropped the area, which was drilled later by others confirming our interpretation.
-3D
3D seismic is often presented as the best progress in seismic exploration, but it is not. The best progress was digital recording, CDP and GPS. 3D is not necessary for finding oil but it is a must to develop a discovery. I do not know any giant field (>500 Mb), which is not seen on 2D. Exxon (Greenslee et al 1994) wrote:" *We found that many surveys (3D) added little values to exploration and development activities*".
3D started more than 30 years ago. The first ones to compute 3D rays with abacus were the Chinese in 1966 (AAPG San Francisco 1981) finding 200 faults in Shengli oilfield when there were few in 2D. The first commercial 3D was in 1972 by GSI. 3D was preceded by the WLP (Wide Line Profiling) from CGG. 3D is a must when the distance between lines decrease and now offshore surveys with more than a dozen streamers 3D are as cheap as 2D. The improvement of the quality of 3D is due to the dense spatial spacing, the right location of the streamers (end at 10 km) with GPS, the small size of the bins and a better processing involving the local geology.
-4D
4D is a 3D repeated after a certain calendar time, the fourth dimension is not continuous, in contrary to the first three. 4D started in the 70s in France with a CGG repetitive 2D (it was in fact a 3D!) on the gas storage of GDF where the gas-water contact was followed, but the change was only of a few milliseconds. 4D is used in the US and in the North Sea to follow the oil-water contact of producing fields by installing permanent seismic arrays (BP, Shell). Because oil discoveries are getting smaller and rarer, it is important to produce the maximum of oil in known fields and to locate oil badly drained as now deviated wells can be drilled with accuracy to any reservoir in a radius of 10 km from a platform.

-workstation
Computers are, like the tongue of Esopus, the best and the worst thing. The huge amount of data now collected can be displayed only with workstations. In the past, interpretation was picked on paper sections and mapping of few horizons done directly by hand. Most giants were found this way. But using workstations, you can be overflooded with data and relying too much on the computer to find anomalies, forgetting the geology. It is not possible to stand all day on a station and during decades. It is necessary to discuss with the geologist and the producer.
-interpretation
The greatest progress in interpretation was done with the introduction of sequence stratigraphy (or seismostratigraphy) by Peter Vail, as geologists started for the first time to look at seismic profiles. The main problem is that geologists believe too much in seismic picking without knowing the full complexity (and inaccuracy and artifacts) of processing.
-other methods (called small methods)
Gravimetry and aeromagnetics were the start of the discovery of many old fields, but they are a little forgotten. Nature is never linear, small methods are often the best way to choose between several solutions brought by seismics.
-field geophysics
Most basins are almost completely explored and Schlumberger, the largest oil services contractor, has closed all its seismic offices in the US onshore. Deepwater discoveries have peaked and are on the decline, and the large deepwater oilfields are restricted to only four countries: Gulf of Mexico, Brazil, Angola and Nigeria all with diapiric tectonic and turbiditic reservoirs. Exploration being on the decline, geophysicists have to work mainly on field development and it is why 4D is so popular
-conclusions
As there is no undiscovered large oil & gas basin, yet-to-discover fields are the ones missed in the past and are more difficult to find: deeper or hidden below the salt or a thrust, or stratigraphic traps, hostile or closed environments. Technology progress must compensate the increase of complexity of new prospects. Geophysics has done tremendous progress in the last 50 years, but less than anticipated, happily for the young geophysicists. It is why it is so thrilling to be geophysicist: there is always something to discover.
Forgive me if I have forgotten or misinterpreted the past, but my power to forget has improved considerably with age.

References:

-Anderson R.N et al 1994 “4D Seismic Imageing of the Drainage and Migration Pathways of Hydrocarbons”
-Domenico S.N. 1976 " Effect of brine-gas-mixture on velocity in unconsolidated sand reservoir" Geophysics 41 p882-894
-Greenslee S.M., G.M.Gaskins, M.G.Johnson 1994 "3-D seismic benefits from exploration through development: an Exxon perspective" The leading edge -July -p730-734
-Laherrère J.H. 1961 “Utilisation pratique des films synthétiques dans le Sahara Nord” Geoph. Prosp. v9 n°1, p46-59
-Laherrère J.H. , R.D.Drayton 1965 “Some geophysical results across the Simpson Desert” The Australian Petroleum Exploration Association Journal- p48-58
--Laherrère J.H. 2000 "Oceanic hydrates: more questions than answers" Energy Exploration & Exploitation, Special issue on hydrates, printing
-Dunoyer de Segonzac Ph., Laherrère J.H. 1959 “Application of the continuous velocity log to anisotropy measurements in Northern Sahara: results and consequences” Geoph. Prosp. v7 n°2, p202-217